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CANADIAN SILICA RESOURCES: A STUDY OF THE PROCESSING OF SELECTED QUEBEC SILICA SAMPLES FOR GLASS AND FOUNDRY SAND

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by

R.K. Collings* and P.R.A. Andrews**

SUMMARY

In co-operation with the Ministère de l'Energie et des Resources, Quebec, the Centre de Recherches Minérales, St. Foy, and various silica producers, selected deposits of Quebec silica were identified in the southern region of the province and sampled to provide material for evaluation as glass and foundry sand by CANMET. The samples included both sandstone and quartz/quartzite. Head sample analyses ranged from 94.66 to 99.54% SiO_2, 0.038 to 0.230% Fe_2O_3, and 0.16 to 4.51% Al_2O_3.

Impurities included pyrite, iron oxides, and iron staining on quartz grains; carbonates as calcite; and aluminium oxide as clay and/or feldspar. Benefication included size reduction to grain size, about 600 µm, by jaw, roll and cone crushers, and grinding in a muller-mixer. Removal of fines was achieved by attrition scrubbing and washing. Further removal of impurities was achieved by reverse flotation of iron oxide and alumino-silicate minerals employing both anionic and cationic collectors. Flotation resulted in a substantial improvement in the quality of most samples, the quartz concentrates analysing 99.08 to 99.80% SiO_2, 0.014 to 0.048% Fe_2O_3, and 0.06 to 0.49% Al_2O_3. Removal of iron oxide minerals was also investigated using the Sala HGMS. Iron oxide analyses of the non-magnetic fractions were similar to the iron oxide analyses of the quartz concentrates obtained by flotation, 0.013 to 0.054% Fe_2O_3. On the basis of the samples submitted, silica from 5 of the 6 deposits studied has potential as source material for glass sand. Foundry tests showed that 3 of the 4 samples submitted for evaluation have potential as foundry sand.

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RESSOURCES CANADIENNES EN SILICE: ÉTUDE DU TRAITEMENT D'ÉCHANTILLONS SELECTIONNÉS DE SILICE DU QUÉBEC, POUVANT SERVIR À LA FABRICATION DU VERRE, OU DE SABLE DE FONDERIE

par

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RÉSUMÉ

En collaboration avec le Ministère de l'Énergie et des Ressources du Québec, le Centre de recherches minérales de St-Foy et divers producteurs de silice, on a identifié dans la région sud de la province certains gisements de silice, dont on a prélevé des échantillons à des fins d'évaluation; le CANMET doit déterminer leurs possibilités d'utilisation comme sable de fonderie, ou dans la fabrication du verre. Les écantillons comprenaient à la fois des grès et du quartz ou des quartzites. À l'analyse, les écantillons minéraux prélevés ont donné 94,66 à 99,54 % de SiO_2, 0,038 à 0,23 % de F_2O_3 et 0,16 à 4,51 % de Al_2O_3.

Parmi les impuretés, citons la pyrite, les oxydes de fer et des taches ferrugineuses sur les grains de quartz; des carbonates sous forme de calcite, et des oxydes d'aluminium sous forme d'argile, de feldspath, ou des deux à la fois. Le processus d'enrichissement comprenait la comminution jusqu'à 600 µm au moyen de concasseurs à mâchoires, à rouleaux et à cônes, et le broyage dans un malaxeur pour sables de fonderie. On a éliminé les fines par lavage à l'eau et lavage par attrition et enlevé davantage d'impuretés par flottation inverse des oxydes de fer et des minéraux alumino-silicatés dans les collecteurs anioniques et des collecteurs cationiques. La flottation a permis d'améliorer substantiellement la qualité de la plupart des échantillons; à l'analyse,

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les concentrés de quartz ont donné 99,08 à 99,80 % de SiO_2, 0,014 à 0,048 % de Fe_2O_3 et 0,49 % de Al_2O_3.

On a aussi étudié l'élimination des divers oxydes de fer à l'aide du séparateur magnétique de gradient élevé SALA. Pour les fractions non magnétiques, le dosage des divers oxydes de fer a donné les mêmes résultats que pour les concentrés quartzeau obtenus par flottation, soit 0,013 à 0,054 % de F_2O_3. D'après les échantillons analysés, la silice de cinq gisements sur six étudiés pourrait convenir à la fabrication du verre. Les essais applicables aux sables de fonderie ont montré que trois échantillons sur les quatre soumis à des fins d'évaluation conviendraient à cet usage.

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INTRODUCTION

Canada continues to import significant quantities of high-purity sand, chiefly from the United States, for use in glass manufacture and by the foundry industry. Imports in 1983, for example, were 0.98 Mt valued at $16.9 million[1].

There are a number of potential sources of high-purity silica sand in Canada. This fact and the need for further study was highlighted at the Federal-Provincial Industrial Minerals Seminar that was held in 1980 in Ottawa[2]. Discussions within CANMET following that meeting resulted in a decision to initiate a laboratory study and appraisal of the technical feasibility of producing silica sand for glass and foundry applications from a few of the more attractive deposits for domestic consumption and export. Glass sand specifications usually stipulate that all sand should be between 600 and 100 μm in size, and have the following minimal chemical analyses - 99.6% SiO_2, 0.03% Fe_2O_3, 0.15% Al_2O_3, with low lime and magnesia. Iron and steel foundry sands vary in grain size between 850 and 75 μm in closely sized ranges. AFS (American Foundryman's Society) numbers vary between 55 and 65, with the bulk of the sand preferably being on three adjacent sieves. A rounded grain shape is preferred. The quartz content should be high, 99% SiO_2, with low aluminium, iron, sodium and potassium oxides, the last three acting as fluxing agents.

This 3-year study would be made in cooperation with the provincial governments and was to concentrate on Ontario in the first year, Quebec in the second and, in the third, on selected resources in several of the remaining provinces. The Ontario[3] report was published in 1983. This present report outlines work undertaken on Quebec silica resources during 1983/84. The Ministère de l'Energie et des Resources, Quebec, and the Centre de Recherches Minérales, Sainte Foy,, cooperated fully in this work. Mr. Conrad Paré of the former, and Mr. G.H. Cloutier of the latter organization were of invaluable assistance in this regard.

SOURCE AND DESCRIPTION OF SAMPLES

In May 1983 a meeting was arranged between R.K. Collings and P.R.A. Andrews both of the Non-Metallic Minerals Section, CANMET and G.H. Cloutier and interested staff at the Centre de Recherches Minérales, Sainte-Foy, Quebec, to discuss the proposed study of Quebec silica resources by CANMET. Mr. Cloutier offered to contact producers and owners of selected silica properties to invite them to submit samples to CANMET for study and evaluation. In addition, background information on the deposits, including a description of the samples with locations from which they were obtained, would be supplied. Information relative to the 9 selected samples, from 6 deposits, is summarized in Tables 1 and 2. For ease of reference the original sample identification numbers have been replaced by letters A to I, as shown in Table 1, and throughout this report the samples are identified and referred to by this letter system. Locations of the areas from which samples were obtained are shown on the map, Fig. 1.

SAMPLE PREPARATION AND PROCESSING

In processing sandstone to sand for glass and foundry applications it is important that the parent sandstone is reduced to its natural grain size to free impurities for subsequent removal and, as well, that this be done without excessive fracturing of grains and resulting production of unwanted fines. Whole, unfractured grains are preferred in foundry moulding and fines are detrimental in both foundry and glass applications.

In the previous study of Ontario Potsdam sandstone[3] a comminution procedure involving preliminary reduction by jaw, cone and roll crushers, with final reduction to grain size performed wet in a Simpson muller-mixer, was found to be satisfactory. An examination of crushed products showed a good reduction to grain size with a minimum of agglomerate and fractured grains. Since the Quebec sandstone samples were similar in texture, the same comminution procedure was adopted. Some of the samples, however, were quartz or quartzite and as such do not possess an inherent 'sand-grain' structure. In crushing these samples, therefore, the aim was rather to avoid overcrushing.

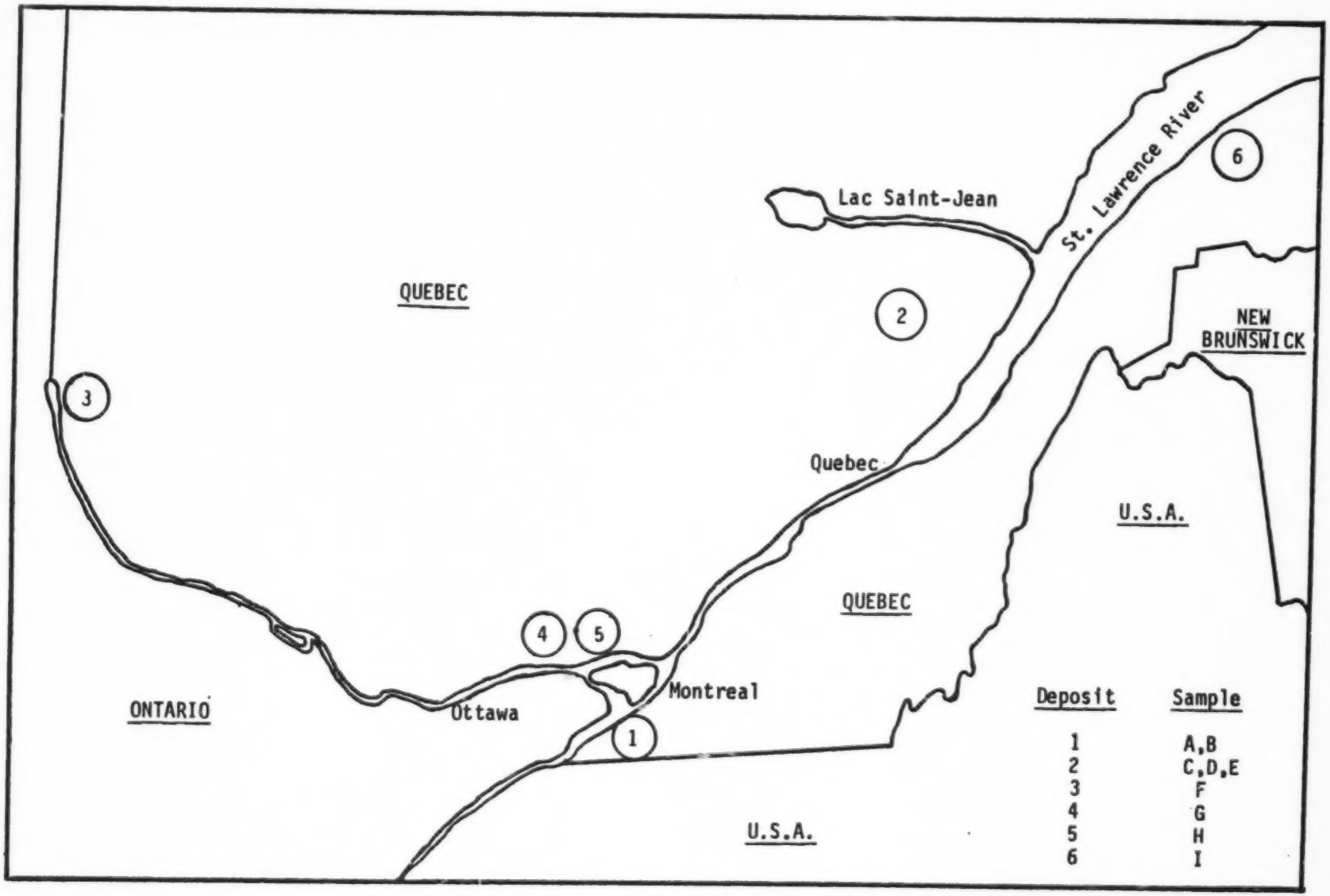

Fig. 1 - Location of silica deposits

The following procedure was therefore used for the reduction of both sandstone and quartz/quartzite samples.

1. Stage crush to 5 mm by jaw crusher, removing -5 mm by screening following each pass.

2. Remove -600 µm sand from jaw crusher product by Sweco screen.

3. Stage crush -5 mm + 600 µm from jaw to 1.5 mm by cone crusher, removing 1.5 mm following each pass.

4. Remove -600 µm from cone product by Sweco screen.

5. Crush -1.5 mm + 600 µm from cone to -600 µm by roll crusher, and riffle out head sample.

6. Combine all products and screen on Sweco at 125 µm.

7. Wet grind (98% solids) + 125 µm product from Sweco to sand size in the Simpson muller-mixer.

CRUSHING AND GRINDING

Using this procedure approximately 20 kg of each sample was crushed, dry-sized at 125 µm to remove unwanted fines, and wet ground in the Simpson muller-mixer for 30 min. This scrubbing and grinding action reduced most of the compound grains to grain size without creating excessive fines.

ATTRITION SCRUBBING

Previous CANMET studies of the processing of sandstone-derived sand demonstrated attrition scrubbing to be an ideal secondary processing step. The intensive scrubbing aids breakdown of clay-bonded compound grains and the removal of coatings and surface staining on the individual quartz particles.

The damp muller-mixer product was scrubbed in a 10 kg capacity, Wemco attrition machine at 80% solids for 20 min. The scrubbed product was then washed and the sands allowed to settle. The slimes were then decanted at 100 μm and the entire procedure repeated. Three washing-settling-decanting cycles were required to free and remove the slimes.

After removal of the slimes, each sample was dried and riffled into 1 kg lots for subsequent flotation studies. A portion was reserved for binocular examination and sieve analysis. Sieve analyses of the washed attrition products are noted in Table 3, and the results of a binocular examination of the washed attrition products in Table 4.

FLOTATION

Removal of small quantities of liberated impurities by flotation is an efficient method of beneficiation. Because silica is the major constituent it is logical to float the impurities by reverse flotation leaving a pure quartz concentrate.

The procedure adopted for removal of impurities was based on the known response of the minerals to flotation. In general flotation practice is to first float iron oxide minerals using a petroleum sulphonate collector followed by cationic flotation using amines to float alumino-silicate minerals. In the previous study[3] the collector Duomeen TDO[4] (n-tallow-1,3-diaminopropane dioleate) was used successfully to float alumino-silicate minerals.

The following general procedure was therefore adopted:

Stage 1. Iron oxide flotation using Aerofloat 840[5] (natural petroleum sulphonate) at pH 3.5-4.0, employing high pulp density (≈50% solids) conditioning.

Stage 2. Alumino-silicate flotation using Duomeen TDO at pH 2.0-2.2, employing high pulp density (≈50% solids) conditioning.

In each stage, high pulp density conditioning was conducted for 5 min with Dowfroth 250 being added as required. Immediately following conditioning the pulp density in each stage was reduced to 30% solids and flotation conducted until completion which was generally 5 min. At the end

of stage 1 the quartz concentrate was filtered and washed twice to remove any residual petroleum sulphonate before repulping and proceeding to stage 2. In some tests, stage 1 was omitted as the petroleum sulphonate collector caused an excessive amount of quartz to be floated, see Table 6.

At the completion of stage 2 all products were filtered, dried and selected products prepared for chemical analysis.

Complete chemical analysis of pre-flotation products and flotation concentrates with % distributions of SiO_2, Al_2O_3 and Fe_2O_3 are presented in Table 5, flotation reagent consumption values in Table 6, and product balances of the best tests in Table 7.

MAGNETIC SEPARATION

A 100-g portion of flotation feed from each of the nine samples was subjected to magnetic separation using the Sala high gradient magnetic separator (HGMS). The current rating was set for maximum separation of iron oxide minerals and the products from each test were analysed for Fe_2O_3. The results, presented in Table 8, show the relative distribution of iron oxide in both the magnetic and non-magnetic fractions. The actual distributions of the non-magnetic products are presented in Table 5 for comparison with flotation recovery performance.

CHEMICAL ANALYSIS

Screening, scrubbing, flotation and magnetic separation involve the production of a large number of products. Some of these required full analysis of identifiable minerals, others required analysis of only one or two minerals, whilst some products did not require analysis.

Based on previous experience, sand products from screening and scrubbing operations need only be analysed, whilst the fines or slime products require only to be weighed.

Flotation involves the removal of small quantities of iron oxide and alumino-silicate minerals, leaving a clean quartz concentrate; only the quartz concentrate need be analysed. Iron oxide and alumino-silicate concentrates from the best test performed on each of the nine samples were, however, analysed for Fe_2O_3 and Al_2O_3 to provide additional information.

The screened sand and attrition scrubbed sand products, flotation feed and flotation quartz concentrates were analysed for:

SiO_2, Fe_2O_3, Al_2O_3, CaO, MgO, LOI

The iron oxide and alumino-silicate concentrates from the best tests were analysed for Fe_2O_3 and Al_2O_3 and magnetic separation products for Fe_2O_3.

The analytical methods employed were wet chemical for SiO_2 and LOI; spectrographic for Fe_2O_3, Al_2O_3, CaO and MgO. The lower limit for Al_2O_3 detection, however, is only 0.06%, so that analyses less than this value are reported as 0.06%.

FOUNDRY EVALUATION

The work was limited to the preparation of "standard" sand/clay/water mixtures using submitted samples, B, F, H and I and the determination of selected moulding properties of these mixes. In addition, quantities permitting, one small step block mould was prepared with each, and these in turn poured with mild steel at 1620°C.

The mixes were prepared in a small, 457 mm diameter laboratory muller. The quantities of additives, given in Table 9, were based on the amount of sand. Moisture was determined on the mix and thus is the true weight percentage of the total. The moulding properties of the sand/clay/water, i.e. the properties of the "green" sand mixes are shown with "typical" results obtained in previous studies using Ottawa silica sand. It is to be noted that the values given are the arithmetic average of three consecutive tests.

Samples C, D and E were not submitted for evaluation as foundry sand because the angularity of the grains would discourage use of such sands for moulding purposes.

RESULTS AND EVALUATION

CRUSHING, GRINDING AND SCRUBBING

Examinations of products from each stage of crushing and of the sized fractions from the Wemco attrition scrubber indicated that the various

stages of size reduction generally reduced the Potsdam sandstone samples, A, B, G, H and I, to grain size without excessive fracturing of grains and production of unwanted waste fines. Product weight recoveries, noted in Table 5, show recovery of -600 + 100 µm sand from the attrition scrubber averaged 88.28 % wt and ranged from 84.90 % wt for sample I to 91.49 % wt for sample G. Most samples had a fairly uniform grain size with the bulk of the material being in the -600 + 150 µm range; sample I, a more siliceous sandstone, was more finely divided than the others due perhaps to overcrushing. The products generally had relatively small percentages of compound and fractured grains; however, grain angularity or sharpness showed a substantial increase in the finer, -100 µm sizes.

Sample F, which essentially consisted of clay-bonded quartz agglomerates with a substantial percentage of "free" sand, was overcrushed. As noted under the foundry evaluation section, it would have been preferable to remove and discard the coarse quartz agglomerates and use only the remaining sand, about 50% of the sample, for processing and evaluation as foundry sand.

Samples C, D and E, being quartzitic in nature, as expected generally produced sharply angular grains on crushing and excess losses to fines, 27.1, 21.1 and 21.8% wt respectively for the scrubbed attrition product.

Attrition scrubbing and washing successfully removed adhering fines from the quartz grains prior to flotation. All attrition products were of a good white colour.

FLOTATION

In general, iron oxide and alumino-silicates responded well to flotation. For convenience and ease of observation, the analysis values of quartz concentrates for the best test obtained with each sample are summarized as follows.

Sample Identification	Test No	Analysis %						Distrib %
		SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	LOI	SiO_2
A	4	99.61	0.048	0.06	0.05	0.028	0.18	85.08
B	28	99.60	0.036	0.06	0.01	0.01	0.33	72.03
C	8	99.20	0.014	0.13	0.01	0.01	0.17	70.49
D	19	99.40	0.029	0.09	0.01	0.01	0.04	73.71
E	22	99.55	0.016	0.07	0.01	0.01	0.04	73.21
F	25	99.08	0.047	0.49	0.01	0.01	0.17	73.00
G	13	99.32	0.029	0.06	0.01	0.016	0.15	86.18
H	31	99.77	0.028	0.09	0.01	0.01	0.19	89.30
I	33	99.80	0.022	0.06	0.01	0.01	0.10	79.38

The range of iron oxide is from 0.014 to 0.048% Fe_2O_3 which is within range of the 0.03% Fe_2O_3 specification for glass sand. Further reduction of the higher levels could be achieved by acid leaching. With regard to Al_2O_3 content, the analysis range achieved was, with the exception of Sample F, 0.06 to 0.13% Al_2O_3 which is below the 0.15% Al_2O_3 specification for glass sand.

Each of the best test results was chosen mainly with regard to analysis rather than recovery although the SiO_2 recovery levels are quite acceptable, as shown in the summary.

Most samples responded to iron oxide and alumino-silicate flotation in the usual manner, that is, flotation of a small quantity of mineral. Samples D, E and H, however, responded unselectively to iron oxide flotation in that excessive amounts of quartz in these samples were floated by the petroleum sulphonate collector. The reason for this behaviour was not examined. All three samples responded to alumino-silicate flotation in the expected manner.

The reagent consumption for iron oxide and alumino-silicate flotation ranged from 80 to 180 g/t. The majority of tests were performed using 130 g/t of both Aerofloat 840 and Duomeen TDO, as shown in Table 10.

MAGNETIC SEPARATION

The performance of magnetic separation in separating iron oxide minerals is comparable to the removal of iron oxide minerals by flotation as the following comparison between the two methods shows:

Sample Identification	Flotation (Qtz_2 conc)		Mag. Sepn (Non-mag. product)	
	Test No	Analysis % Fe_2O_3	Test No	Analysis % Fe_2O_3
A	4	0.048	35	0.048
B	28	0.036	36	0.054
C	8	0.014	37	0.013
D	19	0.029	38	0.014
E	22	0.016	39	0.013
F	25	0.047	40	0.027
G	13	0.029	41	0.047
H	31	0.028	42	0.024
I	33	0.022	43	0.014

For samples A, C, E and H the quartz concentrate analyses are virtually equal to the non-magnetic product analyses; for samples B & G the non-magnetic product analyses are higher than the quartz concentrate analyses, and for samples D, F and I the non-magnetic product analyses are lower than the quartz concentrate analyses.

FOUNDRY EVALUATION

The results given in Table 9 show that with the exception of the mouldability index, the properties obtained with the sands approach the range properties obtained when mixing Ottawa silica sand in a similar manner and formulation. The mouldability index in these instances could have been adjusted to a "desired" value of 75 with increased moisture content; however, in this limited series of tests, the "rule-of-thumb" of 2:1 w:w clay/water was adhered to.

Castings made with three of the submitted samples, B, H, I, were of acceptable quality and surface, the surface(s) being free from burnt-on sand and commensurate with the grain fineness of the provided samples. Sample F did not perform satisfactorily, but showed pronounced "burn-on". The sand adhering to the casting required lengthy grit blasting before the metal surface was reached.

It is interesting to note that sand samples B, H and I were formed from Potsdam sandstone and that the produced sand had rounded to sub-rounded grains. By constrast, sample F was essentially a rather coarse sand which, on crushing, produced a large percentage of sharply angular grains. A more acceptable sand undoubtedly would have been produced with sample F had the coarser, + 600 µm sand been discarded rather than crushed and included with the finer size of sand. Samples A and G, although not included in the foundry test series, were similar to samples B and H respectively, being Potsdam sandstones with rounded to sub-rounded grains. It is probable that these two sands would have performed equally as well as samples B and H in foundry tests. Thus 5 of the 9 samples studied could have some application as foundry sand.

CONCLUSION

On the basis of the samples submitted, silica from 5 of the 6 deposits included in this study (1,2,4,5 and 6, Table 1), has potential as source material for glass sand; that from deposit No. 3, continued to contain excessively high alumina even following intensive processing. Three of the four samples submitted for foundry sand evaluation (sample B, deposit 1; sample H, deposit 5; and sample I, deposit 6) compared favourably with standard Ottawa sand. Sample F, from deposit 3, was overcrushed. It is likely that foundry results would have been more impressive had tests been conducted on only the -600 µm portion of the scrubbed head sample. Samples A and G, which are generally similar to samples B and H, respectively, also could be expected to compare favourably with Ottawa sand in moulding and casting tests.

Further research with larger, more representative samples is recommended to more fully determine the potential of these silica deposits as source material for glass and foundry sand.

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TABLE 1 - Sample identification and location

Identification	Sample	Location	
83/7-1	A	Sainte-Clotilde, Comté de Chateauguay	(deposit No. 1)
83/7-2	B	Sainte-Clotilde, Comté de Chateauguay	(deposit No. 1)
83/9	C	Petit Lac Malbaie, Comté de Charlevoix	(deposit No. 2)
83/11-1	D	Petit Lac Malbaie, Comté de Charlevoix	(deposit No. 2)
83/11-2	E	Petit Lac Malbaie, Comté de Charlevoix	(deposit No. 2)
83/12	F	Saint-Bruno de Guigues, Comté de Témiscamingue	(deposit No. 3)
83/14-1	G	Saint-Canut, Comté de deux-montagnes	(deposit No. 4)
83/14-2	H	Saint-Canut, Comté de deux-montagnes	(deposit No. 5)
83/15	I	Val-Brillant, Rivière Matane	(deposit No. 6)

TABLE 2 - Sample description

Sample	Physical description	Type of sand
A	Crushed drill core sections from D.D.H. 1,2,5 and 11; 0 to ≈12.2 m interval selected from each D.D.H. for further study; all four combined for investigation; white to gray, siliceous sandstone with minor shale, iron oxide, carbonate; possibly some pyrite and feldspar (alumina).	Potsdam sandstone
B	Waste crusher fines, not as pure as Sample A but similar in composition.	Potsdam sandstone
C	-25 mm gray to white, crushed quartz, very friable but with an angular grain shape; minor mica, and possibly feldspar, with occassional unidentified brown particles; not suitable as foundry sand.	Quartz/quartzite
D	-25 mm gray to light brown, crushed quartz, friable but with an angular grain shape; mica impurity and fine, clay-like coatings on some grains; not suitable as foundry sand. Possibility of iron contamination noted.	Quartz/quartzite
E	-20 mm gray to white, crushed quartz, friable but with an angular grain shape; similar to sample D in composition; not suitable as foundry sand; rejects from D.D.H. and channel sampling.	Quartz/quartzite
F	-25 mm to sand size, sand loosely bonded with kaolin; yellow mineral grains identified as muscovite mica.	Clay-bonded quartz agglomerates
G	-150 mm white to gray, siliceous sandstone lumps; impurities include kaolin, minor pyrite plus iron oxide.	Potsdam sandstone
H	-50 mm white to gray, siliceous sandstone lumps; impurities generally similar to sample G.	Potsdam sandstone
I	-150 mm fine grained, siliceous sandstone lumps; impurities include kaolin, dark quartz, possibly some pyrite and some iron staining.	Potsdam sandstone

TABLE 3 - Sieve analyses of washed attrition products

Size (μm)	Direct % wt								
	A	B	C	D	E	F	G	H	I
-630 + 400	1.9	2.7	4.0	3.2	2.0	11.9	6.8	2.8	3.7
-400 + 315	13.4	15.7	15.8	12.4	10.1	21.9	21.5	12.1	14.2
-315 + 200	48.1	47.2	33.8	28.7	29.0	33.8	44.1	38.2	30.6
-200 + 160	15.7	14.4	13.0	13.2	14.1	10.8	11.7	18.1	13.4
-160 + 100	16.2	14.3	22.2	24.6	25.0	14.2	12.9	20.6	21.9
-100 + 71	3.6	4.1	8.7	12.0	12.6	5.1	2.5	5.8	9.7
- 71 + 50	0.9	1.2	2.2	5.0	5.7	1.7	0.5	1.9	4.8
- 50	0.2	0.4	0.3	0.9	1.5	0.6	0.0	0.5	1.7
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Size (μm)	Cumulative % wt passing								
	A	B	C	D	E	F	G	H	I
-630 + 400	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
-400 + 315	98.1	97.3	96.0	96.8	98.0	88.1	93.2	97.2	96.3
-315 + 200	84.7	81.6	80.2	84.4	87.9	66.2	71.7	85.1	82.1
-200 + 160	36.6	34.4	46.4	55.7	58.9	32.4	27.6	46.9	51.5
-160 + 100	20.9	20.0	33.4	42.5	44.8	21.6	15.9	28.8	38.1
-100 + 71	4.7	5.7	11.2	17.9	19.8	7.4	3.0	8.2	16.2
- 71 + 50	1.1	1.6	2.5	5.9	7.2	2.3	0.5	2.4	6.5
- 50	0.2	0.4	0.3	0.9	1.5	0.6	-	0.5	1.7

TABLE 4 - Examination of washed attrition products

Sample	Size fraction and description		
	+300 μm	-300, +150 μm	-150 μm
A	white, rounded to sub-rounded quartz grains, minor percentage of compound grains; minor iron/ iron staining, pyrite	similar to +300 μm, some evidence of broken grains	similar to -300, +150 μm but with increasing percentage of broken, angular-shaped particles; tendency for dark mineral impurity, including pyrite, to concentrate in finer sizes
B	similar to A	similar to A	similar to A
C	clear quartz (quartzite) particles, sharply angular	similar to +300 μm, minor iron pick-up	concentration of dark impurities in finer sizes; needle-like, brown mineral; metallic particles, probably pick-up iron
D	clear quartz (quartzite) particles, sharply angular, minor impurities including mica and pick-up iron	similar to +300 μm, impurities include a black, shiny unidentified mineral	some tendency for dark metallics and other impurities to concentrate in finer sizes
E	similar to D but with larger percentage of impurity including mica and metallic particles and pick-up iron	similar to +300 μm	similar, some concentration of impurities in finer sizes
F	sub-rounded to angular grains of quartz, few compound grains, 2 or 3% of green to brown muscovite mica, minor percentage of other minerals	similar to +300 μm, greater percentage of angular grains	similar, greater percentage of angular grains, little percentage increase in muscovite
G	rounded to sub-rounded quartz grains, minor percentage of compound grains, minor impurities with some pyrite and iron oxide staining	similar to +300 μm, some pyrite and iron impurity	similar to -300, +150 μm, grains more sharply angular, tendency for pyrite to concentrate in finer sizes
H	similar to G but with less pyrite	similar to G but with less pyrite	similar to G but with less pyrite
I	frosted, rounded to sub-rounded quartz grains, minor impurities	similar to +300 μm, but with greater percentage of fractured grains	similar to -300 + 150 μm, angularity of grains increase in finer sizes, minor impurities

TABLE 5 - Sample A: Chemical analyses with product distributions for SiO_2, Fe_2O_3 and Al_2O_3

Products	Wt %	Analysis %							Distribution %		
		SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	LOI	TOTAL	SiO_2	Fe_2O_3	Al_2O_3
Head sample	100.00	98.08	0.11	0.30	0.47	0.14	0.61	99.87	100.00	100.00	100.00
Sweco screen											
-600 + 125 µm	94.05	98.46	0.10	0.26	0.45	0.15	0.54	99.96	94.41	85.55	81.50
- 125 µm	5.95										
Wemco scrubbing											
-600 + 125 µm	90.95	98.63	0.076	0.08	0.30	0.09	0.44	99.62	91.46	68.18	24.27
- 125 µm	3.10										
Flotation concns											
Test 4	83.77	99.61	0.048	0.06	0.05	0.028	0.18	99.98	85.08	36.55	16.77
5	90.04	99.39	0.053	0.06	0.08	0.042	0.16	99.79	91.24	43.36	18.00
6	79.55	99.25	0.042	0.06	0.02	0.020	0.19	99.58	78.95	30.36	15.90
10	90.63	99.21	0.049	0.06	0.07	0.045	0.15	99.58	91.67	40.37	18.13
Non-magnetic product											
Test 35	86.36	---	0.048	---	---	---	---	---	---	37.68	----

TABLE 5 (cont'd) - Sample B: Chemical analyses with product distributions for SiO_2, Fe_2O_3 and Al_2O_3

Products	Wt %	Analysis %							Distribution %		
		SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	LOI	TOTAL	SiO_2	Fe_2O_3	Al_2O_3
Head sample	100.00	97.94	0.18	0.40	0.34	0.13	0.44	99.43	100.00	100.00	100.00
Sweco screen											
-600 + 125 µm	94.36	98.31	0.15	0.37	0.27	0.10	0.36	99.56	94.72	78.61	87.28
- 125 µm	5.64										
Wemco scrubbing											
-600 + 125 µm	84.98	98.97	0.092	0.14	0.16	0.048	0.26	99.67	85.87	43.44	29.75
- 125 µm	9.38										
Flotation concns											
Test 26	83.78	99.50	0.051	0.10	0.02	0.02	0.12	99.81	85.12	23.72	20.95
27	81.78	99.59	0.052	0.08	0.01	0.01	0.15	99.89	83.16	23.61	16.35
28	70.83	99.60	0.036	0.06	0.01	0.01	0.33	100.05	72.03	14.17	10.63
Non-magnetic product											
Test 36	80.86	---	0.054	---	---	---	---	---	---	24.26	---

TABLE 5 (cont'd) - Sample C: Chemical analyses with product distributions for SiO_2, Fe_2O_3 and Al_2O_3

Products	Wt %	Analysis %							Distribution %		
		SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	LOI	TOTAL	SiO_2	Fe_2O_3	Al_2O_3
Head sample	100.00	98.52	0.048	0.66	0.010	0.014	0.27	99.52	100.00	100.00	100.00
Sweco screen											
-600 + 125 µm	89.47	98.72	0.042	0.42	0.008	0.011	0.22	99.42	89.65	78.33	56.94
- 125 µm	10.53										
Wemco scrubbing											
-600 + 125 µm	72.93	99.17	0.021	0.18	0.006	0.009	0.14	99.53	73.41	31.88	19.89
- 125 µm	16.54										
Flotation concns											
Test 7	71.08	99.39	0.025	0.13	0.01	0.01	0.16	99.73	71.71	37.08	14.00
8	70.01	99.20	0.014	0.13	0.01	0.01	0.17	99.53	70.49	20.42	13.79
Non-magnetic product											
Test 37	71.38	---	0.013	---	---	---	---	---	---	19.33	---

TABLE 5 (cont'd) - Sample D: Chemical analyses with product distributions for SiO_2, Fe_2O_3 and Al_2O_3

Products	Wt %	Analysis %							Distribution %		
		SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	LOI	TOTAL	SiO_2	Fe_2O_3	Al_2O_3
Head sample	100.00	98.85	0.14	0.35	0.02	0.020	0.23	99.61	100.00	100.00	100.00
Sweco screen											
-600 + 125 µm	87.90	99.09	0.14	0.30	0.01	0.024	0.19	99.75	88.11	100.00	75.34
- 125 µm	12.10										
Wemco scrubbing											
-600 + 125 µm	78.95	99.40	0.11	0.09	0.01	0.01	0.10	99.72	79.39	62.03	20.31
- 125 µm	8.95										
Flotation concns											
Test 17	41.60	99.53	0.018	0.06	0.01	0.01	0.09	99.72	41.89	5.35	7.14
18	77.24	99.44	0.056	0.06	0.01	0.01	0.04	99.62	77.70	30.90	13.23
19	73.30	99.40	0.029	0.09	0.01	0.01	0.04	99.58	73.71	15.18	18.86
Non-magnetic product											
Test 38	76.26	---	0.014	---	---	---	---	---	---	7.63	---

TABLE 5 (cont'd) - Sample E: Chemical analyses with product distributions for SiO_2, Fe_2O_3 and Al_2O_3

Products	Wt %	Analysis %							Distribution %		
		SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	LOI	TOTAL	SiO_2	Fe_2O_3	Al_2O_3
Head sample	100.00	98.94	0.12	0.56	0.02	0.021	0.23	99.89	100.00	100.00	100.00
Sweco screen											
-600 + 125 µm	91.02	99.02	0.097	0.39	0.01	0.019	0.24	99.78	91.09	73.58	63.39
- 125 µm	8.98										
Wemco scrubbing											
-600 + 125 µm	78.19	99.15	0.076	0.18	0.01	0.010	0.11	99.54	78.36	49.52	25.13
- 125 µm	12.83										
Flotation concns											
Test 20	45.60	99.55	0.013	0.11	0.01	0.01	0.04	99.73	45.88	4.94	8.96
21	76.31	99.27	0.046	0.12	0.01	0.01	0.06	99.52	76.57	29.25	16.36
22	72.76	99.55	0.016	0.07	0.01	0.01	0.04	99.70	73.21	9.70	9.09
Non-magnetic product											
Test 39	75.09	----	0.013	----	----	----	----	----	----	8.14	----

TABLE 5 (cont'd) - Sample F: Chemical analyses with product distributions for SiO_2, Fe_2O_3 and Al_2O_3

Products	Wt %	Analysis %							Distribution %		
		SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	LOI	TOTAL	SiO_2	Fe_2O_3	Al_2O_3
Head sample	100.00	94.66	0.23	4.51	0.01	0.12	0.81	100.34	100.00	100.00	100.00
Sweco screen											
-600 + 125 µm	100.00	94.72	0.25	4.16	0.02	0.11	0.51	99.77	100.00	100.00	92.24
- 125 µm	-										
Wemco scrubbing											
-600 + 125 µm	70.90	98.37	0.062	0.92	0.007	0.023	0.38	99.76	73.63	17.58	14.46
- 125 µm	29.10										
Flotation concns											
Test 23	69.75	98.98	0.044	0.68	0.01	0.014	0.15	99.88	72.93	13.35	10.52
24	69.83	98.95	0.044	0.60	0.01	0.013	0.16	99.78	73.00	13.35	9.29
25	69.74	99.08	0.047	0.49	0.01	0.01	0.17	99.81	73.00	14.26	7.58
Non-magnetic product											
Test 40	66.19	----	0.027	----	----	----	----	----	----	7.77	----

TABLE 5 (cont'd) - Sample G: Chemical analyses with product distributions for SiO_2, Fe_2O_3 and Al_2O_3

Products	Wt %	Analysis %							Distribution %		
		SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	LOI	TOTAL	SiO_2	Fe_2O_3	Al_2O_3
Head sample	100.00	99.03	0.08	0.23	0.03	0.028	0.15	99.55	100.00	100.00	100.00
Sweco screen											
-600 + 125 µm	93.33	99.34	0.078	0.26	0.03	0.024	0.16	99.89	93.62	91.00	100.00
- 125 µm	6.67										
Wemco scrubbing											
-600 + 125 µm	91.49	99.38	0.059	0.07	0.02	0.012	0.12	99.66	91.81	67.50	27.83
- 125 µm	1.84										
Flotation concns											
Test 11	90.50	99.28	0.045	0.06	0.02	0.016	0.13	99.55	90.73	50.88	23.61
12	89.37	99.36	0.034	0.06	0.01	0.015	0.15	99.63	89.67	38.00	23.30
13	85.93	99.32	0.029	0.06	0.01	0.016	0.15	99.59	86.18	31.13	22.44
14	79.34	99.30	0.029	0.06	0.01	0.010	0.09	99.50	79.56	28.75	20.70
Non-magnetic product											
Test 41	87.72	----	0.047	----	----	----	----	----	----	51.54	-----

TABLE 5 (cont'd) - Sample H: Chemical analyses with product distributions for SiO_2, Fe_2O_3 and Al_2O_3

Products	Wt %	Analysis %							Distribution %		
		SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	LOI	TOTAL	SiO_2	Fe_2O_3	Al_2O_3
Head sample	100.00	99.15	0.038	0.33	0.01	0.01	0.21	99.75	100.00	100.00	100.00
Sweco screen											
-600 + 125 µm	97.06	99.20	0.037	0.32	0.01	0.012	0.26	99.84	97.11	94.47	94.12
- 125 µm	2.94										
Wemco scrubbing											
-600 + 125 µm	89.08	99.56	0.029	0.10	0.01	0.01	0.15	99.86	89.45	67.90	27.00
- 125 µm	7.98										
Flotation concns											
Test 29	80.69	99.73	0.032	0.09	0.01	0.01	0.29	100.16	81.16	67.90	22.00
30	64.64	99.72	0.024	0.07	0.01	0.01	0.23	100.06	65.01	40.79	13.73
31	88.74	99.77	0.028	0.09	0.01	0.01	0.19	100.10	89.30	65.53	24.21
32	88.71	99.69	0.029	0.11	0.01	0.01	0.11	99.96	89.19	79.47	61.82
Non-magnetic product											
Test 42	85.81	----	0.024	----	----	----	----	----	----	54.20	----

TABLE 5 (cont'd) - Sample I: Chemical analyses with product distributions for SiO_2, Fe_2O_3 and Al_2O_3

Products	Wt %	Analysis %							Distribution %		
		SiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	LOI	TOTAL	SiO_2	Fe_2O_3	Al_2O_3
Head sample	100.00	99.54	0.038	0.16	0.01	0.027	0.18	99.96	100.00	100.00	100.00
Sweco screen											
-600 + 125 µm	96.09	99.60	0.039	0.10	0.01	0.030	0.15	99.93	96.15	98.68	60.06
- 125 µm	3.91										
Wemco scrubbing											
-600 + 125 µm	84.90	99.52	0.030	0.08	0.01	0.014	0.19	99.84	84.88	67.11	42.44
- 125 µm	11.19										
Flotation concns											
Test 33	79.17	99.80	0.022	0.06	0.01	0.01	0.10	100.00	79.38	45.79	29.69
34	78.62	99.81	0.033	0.06	0.01	0.01	0.16	100.08	78.83	68.42	44.25
Non-magnetic product											
Test 43	81.76	----	0.014	----	----	----	----	----	----	30.12	----

TABLE 6 - Flotation reagent concentrations

Sample	Test No	Iron Oxide Float				Alumino-silicate Float			
		pH	% Wt floated	Aero 840** g/t	Dow 250** g/t	pH	% Wt floated	Duo TDO** g/t	Dow 250 g/t
A	4	4.0-4.5	7.54	130	60	2.04-2.20	0.34	130	60
	5	3.5-4.0	0.89	80	60	2.06-2.33	0.11	80	60
	6	3.5-4.0	10.95	180	60	2.00-2.27	1.58	180	60
	10					2.00-2.18	0.35	130	48
B	26	3.5-4.0	1.19	80	50	1.86-2.00	0.22	80	50
	27	3.5-4.0	2.93	130	50	1.99-2.23	0.83	130	50
	28	3.5-4.0	13.45	180	50	2.00-2.28	3.20	180	50
C	7	3.5-4.0	1.42	80	60	1.85-2.20	0.01	80	60
	8	3.5-4.0	3.94	130	50	1.99-2.23	0.07	130	50
D	17	3.5-4.0	46.39	80	72	1.95-2.14	0.91	80	72
	18					2.00-2.21	2.16	80	72
	19					1.97-2.23	7.15	130	73
E	20	3.5-4.0	40.96	80	70	2.03-2.27	0.71	80	70
	21					1.98-2.13	2.41	80	70
	22					2.01-2.27	6.94	130	70
F	23	3.5-4.0	1.19	80	70	1.98-2.23	0.44	80	70
	24	3.5-4.0	0.99	130	50	2.00-2.27	0.52	130	50
	25*	3.5-4.0	0.46	130	40	2.03-2.22	1.17	130	50
G	11	3.5-4.0	0.99	80	36	1.94-2.16	0.09	80	47
	12	3.5-4.0	2.14	130	47	2.00	0.17	130	71
	13	3.5-4.0	5.07	180	71	2.00	1.00	180	71
	14	3.5-4.0	9.77	250	71	2.00	3.51	250	71
H	29	3.5-4.0	9.34	80	50	2.02-2.30	0.08	80	50
	30	3.5-4.0	26.74	120	50	1.99-2.24	0.70	120	50
	31					1.99-2.26	0.38	80	50
	32					1.98-2.26	0.42	130	50
I	33	3.5-4.0	6.24	80	50	2.00-2.27	0.50	80	50
	34	3.5-4.0	5.64	50	50	1.99-2.28	1.76	120	50

* Deslimed prior to iron oxide float

**Abbreviated chemical trade names are: Aerofloat 840, Dowfroth 250 and Duomeen TDO respectively.

TABLE 7 - Product balances for selected best tests

Sample	Test	Products	Wt %	Analysis %		Rel. Dist. %	
				Fe_2O_3	Al_2O_3	Fe_2O_3	Al_2O_3
A	4	Iron oxide float	6.86	0.23	0.42	24.96	34.66
		Alumino-silicate float	0.31	2.36	1.30	11.53	4.81
		Quartz conc	83.77	0.048	0.06	63.51	60.53
		Calculated head	90.95	0.070	0.09	100.00	100.00
B	28	Iron oxide float	11.43	0.27	0.21	47.69	29.56
		Alumino-silicate float	2.72	0.31	0.54	12.96	18.10
		Quartz conc	70.83	0.036	0.06	39.35	52.34
		Calculated head	84.98	0.076	0.10	100.00	100.00
C	8	Iron oxide float	2.87	0.18	1.40	33.33	29.73
		Alumino-silicate float	0.05	1.27	7.90	3.85	2.96
		Quartz conc	70.01	0.014	0.13	62.82	67.31
		Calculated head	72.93	0.021	0.19	100.00	100.00
D	19	Alumino-silicate float	5.65	1.21	1.20	76.25	50.67
		Quartz conc	73.30	0.029	0.09	23.75	49.33
		Calculated head	78.95	0.11	0.17	100.00	100.00
E	22	Alumino-silicate float	5.43	0.77	2.10	78.36	69.13
		Quartz conc	72.76	0.016	0.07	21.64	30.87
		Calculated head	78.19	0.068	0.21	100.00	100.00

TABLE 7 - (Cont'd)

Sample	Test	Products	Wt %	Analysis %		Rel. Dist. %	
				Fe_2O_3	Al_2O_3	Fe_2O_3	Al_2O_3
F	25	Slimes	0.78	0.40	4.35	6.54	5.82
		Iron oxide float	0.33	1.04	14.39	7.17	8.15
		Alumino-silicate float	0.83	1.02	19.67	17.93	28.03
		Quartz conc	68.96	0.047	0.49	68.36	58.00
		Calculated head	70.90	0.067	0.82	100.00	100.00
G	13	Iron oxide float	4.64	0.38	0.094	36.00	7.26
		Alumino-silicate float	0.92	0.69	0.50	13.08	7.59
		Quartz conc	85.93	0.029	0.06	50.92	85.15
		Calculated head	91.49	0.057	0.06	100.00	100.00
H	31	Alumino-silicate float	0.34	0.98	0.94	11.70	3.85
		Quartz conc	88.74	0.028	0.09	88.30	96.15
		Calculated head	89.08	0.03	0.09	100.00	100.00
I	33	Iron oxide float	5.30	0.20	0.30	35.81	22.70
		Alumino-silicate float	0.43	0.38	0.50	5.41	9.48
		Quartz conc	79.17	0.022	0.06	58.78	67.82
		Calculated head	84.90	0.035	0.08	100.00	100.00

TABLE 8 - Sala magnetic separation tests

Sample	Test	Products	Wt %	Analysis % Fe_2O_3	Distribution %
A	35	Magnetics	4.59	0.48	34.65
		Non-magnetics	86.36	0.048	65.35
		Calculated head	90.95	0.070	100.00
B	36	Magnetics	4.12	0.61	36.54
		Non-magnetics	80.86	0.054	63.46
		Calculated head	84.98	0.081	100.00
C	37	Magnetics	1.55	0.88	34.65
		Non-magnetics	71.38	0.013	65.35
		Calculated head	72.93	0.031	100.00
D	38	Magnetics	2.69	2.57	86.65
		Non-magnetics	76.26	0.014	13.35
		Calculated head	78.95	0.10	100.00
E	39	Magnetics	3.10	1.26	79.96
		Non-magnetics	75.09	0.013	20.04
		Calculated head	78.19	0.063	100.00

TABLE 8 - (Cont'd)

Sample	Test	Products	Wt %	Analysis % Fe_2O_3	Distribution %
F	40	Magnetics	4.72	0.60	61.29
		Non-magnetics	66.19	0.027	38.71
		Calculated head	70.90	0.065	100.00
G	41	Magnetics	3.77	0.33	23.17
		Non-magnetics	87.72	0.047	76.83
		Calculated head	91.49	0.059	100.00
H	42	Magnetics	3.27	0.45	41.64
		Non-magnetics	85.81	0.024	58.36
		Calculated head	89.08	0.040	100.00
I	43	Magnetics	3.14	0.44	54.70
		Non-magnetics	81.76	0.014	45.30
		Calculated head	84.90	0.030	100.00

TABLE 9 - Moulding properties of sand/clay/water mixtures

	Ottawa Silica	Sample B	Sample F	Sample H	Sample I
AFS No.	60	64	62	70	78
Sand, kg*	9.1	9.1	9.1	9.1	9.1
Clay, g (%)	(6.5)	590(6.5)	590(6.5)	590(6.5)	590(6.5)
Cereal, g (%)	(1.5)	91(1)	91(1)	91(1)	91(1)
Moisture w/o**	3.3	3.5	3.4	3.5	3.4
Permeability air**	180-225	152	212	132	104
Mouldability index**	70-76	89	97	88	93
Green compression, kPa**	58.6-68.9	41.4	51.0	44.8	42.8
Green shear kPa**	1.0-1.4	1.0	0.9	1.0	0.9
Green tensile kPa**	5.6-8.6	5.3	6.2	6.1	4.5
Dry compression, kPa**	358-565	386	290	483	283
Packing weight, 2" x 2" h, g	----	150	150	150	145
Mould hardness	----	80	82	80	85
Casting No.:	----	2	3	1	4

* Two mixes prepared
**Arithmetic average

TABLE 10 - Collector concentrations* employed in achieving optimum results

Sample	Test	Iron oxide flotation	Alumino-silicate flotation
A	4	130	130
B	28	180	180
C	8	130	130
D	19	-	130
E	22	-	130
F	25	130	130
G	13	180	180
H	31	-	80
I	33	80	80

*Reported as g/t